Plasmaspheric Material on High-Latitude Open Field Lines

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Abstract. During periods of increased geomagnetic activity, cold and dense plasmaspheric material is observed to drain from the inner magnetosphere toward the dayside magnetopause. Geosynchronous observations have shown that plasmaspheric material may participate in the dayside reconnection; however, predictions of plasmaspheric material passing through the polar region on recently opened field lines have not yet been confirmed. We present evidence for the existence of such plasmaspheric material on high-latitude open magnetic field lines based on our investigations of twenty months of Interball/Hyperboloid observations and eleven months of Polar/TIDE observations. In order to distinguish plasmaspheric material from the low-energy portion of entering magnetosheath plasma, observed phase-space densities are compared with modeled magnetosheath and plasmaspheric phase-space densities. The phase-space density distribution function of magnetosheath ions is estimated from upstream solar wind parameters using the gas dynamic theory. Twenty-one events were found in which Interball passed through open field lines on the dayside during periods of increased geomagnetic activity, two of which show evidence for the presence of plasmaspheric material. Additionally, four such events were identified from the Polar/TIDE database. Although the occurrence frequency is low, evidence of cold plasmaspheric material being transported on high-latitude open field lines does exist.

1. Introduction

The near-Earth region of the magnetosphere populated by dense (10–10^4 cm^{-3}), cold (few eV) plasma is known as the plasmasphere. The plasmaspheric configuration changes size and shape according to the strength of the convection, which is related to the level of geomagnetic activity. Under quiet geomagnetic conditions, flux tubes in the outer plasmasphere remain on closed drift paths for several days before becoming fully refilled with ionospheric plasma. During periods of increased geomagnetic activity, the loaded flux tubes, previously located on closed drift trajectories, find themselves on open drift trajectories, and flow toward the dayside magnetopause to form a drainage plume in the dayside magnetosphere.

Freeman et al. [1977] proposed that plasmaspheric plasma drifting towards the dayside magnetopause could become accelerated and mixed with solar wind plasma at the magnetopause. Plasma flowing along the field lines could then mirror in the ionosphere and exit into the magnetotail. *Elphic et al.* [1997] employed empirical models of high-latitude ionospheric convection and the geomagnetic field to describe the transport of outer plasmasphere flux tubes from the dayside, over the polar cap and into the magnetotail during the early phase of a geomagnetic storm. *Borovsky et al.* [1997a] suggested that the circulation of plasmaspheric plasma into the outer magnetosphere, and subsequent energizing, could explain observations of "super dense" (factor of 3 increase) plasma sheet occurrences. Recently, geosynchronous observations have shown that during times of strong magnetopause compression and erosion, flux tubes loaded with dense plasmaspheric material may participate in the dayside reconnection [*Su et al.,* 2000]. Predictions of plasmaspheric material passing through the polar region on reconnected field lines, however, have not yet been confirmed [*Borovsky et al.,* 1997b].

In this paper, we present evidence from our investigation of plasmaspheric material on high-latitude open magnetic field lines using data from two satellites, the Interball Auroral Probe and Polar.

2. Phase-Space-Density Estimations

Draining plasmaspheric material will mix with magnetosheath plasma during the reconnection process. From observations, the lowest energy (on the order of 10 eV) of the entering magnetosheath is often comparable to the plasmaspheric energy. A difficult part of searching for plasmaspheric material on reconnected field lines is to distinguish plasmaspheric ions from magnetosheath ions. In order to do so, we use the method described below to estimate the expected phase-space density (PSD) distribution functions of magnetosheath and plasmaspheric material for comparison with observed PSDs, which are presented in Section 3.

2.1. Magnetosheath Source

As an initial step, the Tysganenko '96 magnetic field model (T96) [*Tyganenko et al.,* 1996] was employed to map the satellite location to the magnetopause. T96 is a data-based model of the geomagnetospheric magnetic field with an explicitly defined realistic magnetopuase [*Tyganenko et al.,* 1995], based on fits to a large number of observed crossing. We then used gas dynamic theory [*Spreiter and Stahara,* 1985; *Stahara et al.,* 1979] to estimate the characteristics of the downstream magnetosheath at the magnetopause from the upstream solar wind parameters obtained by the Wind spacecraft. The gas dynamic theory has been successfully used by *Onsager et al.* [1993, 1995] and *Lockwood et al.* [1994] to reproduce transmitted magnetosheath spectra observed by the DMSP and DE 2 satellites in the cusp, polar cap, and mantle regions. An example of calculated gas-dynamic density, velocity, and temperature contours for steady supersonic solar wind flow past the Earth's magnetosphere is shown in Figure 10 of *Spreiter and Stahara* [1985]. The density contour (normalized by the solar wind density) does not change dramatically when the Mach number (M_S) of the solar wind was greater than 8, which applies to the majority of our observational events. We have chosen to simply adopt the density profile from *Spreiter and Stahara's* Figure 10 for our study. The temperature profile, on the other hand, is highly dependent on M_S. For an estimation of the magnetosheath temperature, we use the following equation from *Stahara et al.* [1979].

$$\frac{T_{sh}}{T_{sw}} = 1 + \left[\left(\frac{\gamma - 1}{2}\right) M_s^2\right]\left[1 - \left(\frac{V_{sh}}{V_{sw}}\right)^2\right]$$

where T_{sh} and T_{sw} are the magnetosheath and solar wind temperatures, and V_{sh} and V_{sw} are magnetosheath and solar wind velocities. We use the specific heat γ = 5/3 here. The magnetosheath distribution function is composed of a core and shell population due to the ion reflection at the shock boundary [e.g., *Gosling and Robson,* 1985], which we model as two Maxwellians:

$$f_{Msh} = n_{core}\left(\frac{m}{2\pi kT_{core}}\right)^{3/2} \exp\left(-\frac{mv^2}{2kT_{core}}\right) + n_{shell}\left(\frac{m}{2\pi kT_{shell}}\right)^{3/2} \exp\left(-\frac{mv^2}{2kT_{shell}}\right)$$

where m and k are the proton mass and Boltzmann's constant, respectively. The total number density is equal to sum of n_{core} (the density of core population) and n_{shell} (the density of shell population). n_{shell} is taken to be 20% of the total magnetosheath density. T_{core} and T_{shell} are the temperatures of core and shell magnetosheath populations, respectively, where T_{shell} ~ $4.6T_{core}$. The density and temperature ratios employed here are based on ISEE observations [*Gosling and Robson,* 1985; *Gosling et al.,* 1989]; however, only the core population contributes to the low-energy portion of magnetosheath PSD distribution function. The estimated peak PSD for magnetosheath ions is typically on the order of 10^8–10^9 km^{-6}s^3, depending on the solar wind parameters. An example of the modeled magnetosheath PSD distribution function is described by the solid line in Figure 1.

2.2. Plasmasphere Source

A Maxwellian distribution function was assumed for plasmaspheric ions. Estimated peak PSDs of plasmaspheric ions with various densities and temperatures are listed in Table 1. The dashed line in Figure 1 is an example of the model plasmaspheric PSD distribution function, where the density = 5 cm^{-3} and the temperature = 5 eV. For a typical plasmaspheric temperature (few to 10 eV), the peak PSD is usually one or two orders higher than the estimated magnetosheath PSDs. However, if plasmaspheric ions are energized (heated) to several tens eV, the peak PSD becomes comparable to magnetosheath PSDs, as shown in the bottom two rows in Table 1. This subject is discussed in more detail in Section 4.

Table 1. Estimated plasmaspheric peak phase space density.

$T_{PS}\backslash N_{PS}$	5 cm^{-3}	10 cm^{-3}
5 eV	3.03×10^{10} s^3 km^{-6}	6.06×10^{10} s^3 km^{-6}
10 eV	1.07×10^{10} s^3 km^{-6}	2.14×10^{10} s^3 km^{-6}
40 eV	1.34×10^{9} s^3 km^{-6}	2.68×10^{9} s^3 km^{-6}
80 eV	4.73×10^{8} s^3 km^{-6}	9.46×10^{8} s^3 km^{-6}

3. Satellite Observations

The data shown in this paper were obtained by the Hyperboloid experiment on board Interball Auroral Probe and the Thermal Ion Dynamics Experiment (TIDE) on board Polar. The apogee and perigee of Interball Auroral Probe are 20,000 km in the northern hemisphere and 700 km in the southern hemisphere, respectively. The apogee and perigee of the Polar spacecraft are 9 R_E in the northern hemisphere and 1.8 R_E in the southern hemisphere, respectively. Only the data collected from apogee passes are used in our survey.

Hyperboloid is a muti-directional mass spectrometer measuring ion distribution functions in the auroral and polar magnetosphere of the Earth in the thermal and suprathermal energy range, ~0–80 eV. A negative potential bias applied to the Hyperboloid entrance surface are used to counteract adverse effects of the spacecraft potential and thus enable ion measurements down to very low energies. The main analyzer of the instrument contains 16 entrance windows in a half-planar field of view. Three-dimensional distributions are measured in one 120-s spacecraft spin period. Further details on the Hyperboloid instrument are provided by *Dubouloz et al.* [1998]. The TIDE ion sensor is designed to provide nearly three-dimensional measurements of core ions in the energy range ~0–400 eV above spacecraft potential in one 6-s satellite spin period. *Moore et al.* [1995] provide further details on the TIDE instrument.

For this study, we have examined twenty months of Interball/Hyperboloid observations and eleven months of Polar/TIDE observations for evidence of cold, dense material on high-latitude open magnetic field lines.

3.1. Hyperboloid Results

In twenty months of Hyperboloid observations, twenty-one events were found, between October 1996 to May 1998, in which Interball Auroral Probe passed through open field lines on the dayside while the geomagnetic activity index (Kp) was 4– or higher. We examined Hyperboloid summary spectrograms in an attempt to identify cases in which cold ions were observed on open flux tubes in addition to ionospheric outflows. The open flux tube regions, where plasma sheet material were absent and magnetosheath material were present, were confirmed by the electron and ion measurements from the ION experiment on board the satellite. We then compared observed ion PSD distribution functions with modeled PSD distributions as described in Section 2. In two of 21 cases, evidence of plasmaspheric material was found by the PSD comparison. These two events are described in detail in the following sections.

3.1.1. March 10, 1998

The top panel of Plate 1 shows the H^+ energy-time spectrogram from 1810 to 1840 UT observed by Hyperboloid averaged over the half-planar field of view. The energy flux is color-coded according to the color bar on the right hand side of the image. Angular spectrograms for energies 0–5, 5–12.5, 12.5–30, and 30–80 eV (going up from the bottom) are shown in the bottom four panels of Plate 1 for the time period from 18:12–18:28 UT. The vertical axis represents the 16 instrument sectors; in this mode of operation were opened one by one implying a higher angular resolution. Squares, crosses, and solid lines indicate the directions parallel, anti-parallel, and perpendicular, respectively, to the local magnetic field.

The satellite flew through the polar cap and entered into the cusp/cleft region at ~18:14 UT, where magnetosheath ions were observed (green isotropic background in Plate 1). A sharp open-closed field line boundary is observed at ~18:30 UT where magnetosheath plasma disappears and cold, dense plasmaspheric ions (≥ 200 cm^{-3}) and hot plasma sheet ions are detected. The plasma sheet ions were observed by the ION experiment, but not shown here. The red strips, appearing periodically with each spin period of the spacecraft (2 minutes), are identified as ionospheric outflows. These outflows appear in the direction anti-parallel to magnetic field (i.e., outward from the ionosphere in the northern hemisphere). The energy of these outflows increases when the satellite enters the cusp region.

Three distinct populations are evident at ~18:24 UT. Ionospheric outflows, with energy greater than 30 eV, are seen in the top panel of Plate 1. An isotropic magnetosheath population is seen in all panels. And third population, with energy ranging from 5 to 30 eV, is observed in directions parallel (square symbols) and perpendicular (solid lines) to the local magnetic field. In Figure 2a, two-dimensional PSD distribution function (top) and one-dimensional cut through this distribution (bottom) are shown for the interval from 18:22:30 to 18:24:30 UT. One the top, the horizontal and vertical axes represent the velocity perpendicular ($V_{\perp}$) and parallel ($V_{\parallel}$) to the magnetic field. The PSD is color-coded according to the color bar on the right. Ionospheric outflows with a parallel velocity of ~ -80 km s^{-1} are seen in the top panel. In the bottom panel, the horizontal and vertical axes represent the perpendicular velocity and PSD, respectively. The filled circles are cuts through the PSDs in the upper pannel, taken at $V_{\parallel} = 0$. The blue and red lines, respectively, represent the modeled magnetosheath and plasmaspheric PSDs. The peak of the estimated magnetosheath PSD (on the order of 10^8 km^{-6}s^3) is two order of magnitude lower or more than the peak of the observed PSDs. To test the sensitivity of the modeled magnetosheath PSD to our procedure, we have adjusted the shell/core ratio of magnetosheath by 20% and/or adjusted the magnetopause location in a range of ± 2 R_E in the GSM x direction; in no case did the modeled PSD rise to 10^{10} km^{-6}s^3.

The observed distribution appears to be composed from two distinct populations. Above $|V_\perp|$ ~ 40 km s^{-1}, the observed PSD is comparable to the modeled magnetosheath distribution; whereas below 40 km s^{-1}, the observed PSD is similar to the estimated plasmaspheric distribution. The plasmaspheric density and temperature in this case were assumed to be 2 cm^{-3} and 2 eV, respectively. Although the density in this case is lower than the typical plasmaspheric density, it is higher than the density in the trough region [*Thomsen et al.,* 1998]. The reconnection and transport proceses may cause plasmaspheric density loss. Since the third population is distinguishable from the field-aligned ionospheric outflows (c.f., Plate 1) and magnetosheath ions (c.f., Figure 2a), we believe this population can be neither magnetosheath nor ionospheric ions; rather, the evidence suggests that these ions must be of plasmaspheric origin and are being transported on reconnected field lines.

3.1.2. December 30, 1997

The Interball Auroral Probe was identified to be in the open field line region from ~17:20 to 19:10 UT based on electron and ion measurements (not shown here) from the ION experiment. During this period of time, plasma sheet ions and electrons were absent and polar rain (i.e., magnetosheath electrons) was observed at energies below 400 eV. No magnetosheath ions were detected at energies above 80 eV. The top panel of Plate 2 shows the H^+ energy-time spectrogram from 17:30 to 18:30 UT (8.2– 12.9 LT) observed by Hyperboloid. Angular spectrograms for energies 30–80, 12.5–30, 5–12.5, and 0–5 eV are shown in the bottom four panels of Plate 2 for the time period from 17:30–17:50 UT. The format of Plate 2 is the same as that of Plate 1, except windows were opened by groups of four.

Two distinct populations are apparent in Plate 2. As in the March 10 event, ionospheric ions are observed flowing upward along the field lines from the ionosphere with an antisuward convective motion (bottom panel). The second population, evident between 17:30 to 18:00 UT, is more isotropic, with a characteristic energy that decreases with increasing invariant latitude (ILAT). This energy dispersion signature is similar to the velocity filter effect on mantle magnetosheath ions, although the average energy here is much lower than the typical magnetosheath energy. High-energy magnetosheath ions might exist, but sunward of the spacecraft orbit. Because of this, Interball would observe only low-energy magnetosheath ions, which have had time to convect antisunward. However, this possibility has been excluded with the following PSD comparison.

In Figure 2b, two-dimensional PSD distribution function (top) and one-dimensional cut through this distribution (bottom) are shown for the interval from 1742 to 1744 UT. The format here is same as that of Figure 2a. On the top, the narrow orange beam with negative parallel velocity (~30^o angle to the vertical axis) is evidence of ionospheric outflows. The peak of the estimated magnetosheath PSD (on the order of 10^9 $km^{-6}s^3$) is an order of magnitude lower or more than the peak of the observed PSDs. The plasmaspheric density and temperature values are assumed to be 1.5 cm^{-3} and 5 eV. The estimated plasmaspehric PSD distribution matches the observed distribution quite well. Based on these comparisons, we believe the isotropic population to be plasmaspheric material.

3.2. TIDE Results

The TIDE data used in our survey were collected from April to May 1996 and from December 1996 to August 1997. For the period from December 1996 to August 1997, we selected apogee passes of the Polar spacecraft that included orbits through open field lines on the dayside while *Kp* was at least 4- or higher. For the two month period of April and May 1996, when the TIDE time-of-flight mass analyzer was functioning properly and the data were well calibrated, we examined data from each apogee pass. The open field line regions were confirmed by the electron and ion measurements from the HYDRA experiment on board the Polar satellite.

We examined detailed PSD distribution functions to identify periods in which cold ions were observed in addition to ionospheric outflows. These cases were then compared with estimated PSD distributions as described in Section 2. Four events from the early Polar mission were found in which plasmaspheric material appeared to exist on high-latitude reconnected field lines. Two of these four events are selected and described below.

3.2.1. April 30, 1996

The Polar satellite flew through the close field line region and entered into the open file line region at ~13:35 UT. The open-closed field line boundary was identified by Polar/HYDRA electron and ion measurements (not shown here). The energy dispersion signature from HYDRA indicated that the magnetosheath energy decreased with increasing latitude from 13:35 to 14:30 UT. A two-dimensional PSD distribution function (top) and one-dimensional cuts (bottom) observed by TIDE from 14:08 to 14:09 UT (averaged over 10 spins) are shown in Figure 3a. Distribution functions similar to this were observed over a period of ~20 minutes from 13:55 to 14:15 UT. In the top panel, the two-dimensional PSD distribution function is a slice through the three-dimensional distribution at $V_Z = -6.6$ km s^{-1}. The V_X axis is parallel to the local magnetic field, with the positive direction toward the ionosphere in the northern hemisphere. The V_Y axis is the direction normal to the Polar orbital plane, with the positive direction toward the dawn and negative toward the dusk. Information on the spacecraft potential, position, L-shell, magnetic local time (mlt), magnetic latitude (mlat), and invariant latitude (invlat) are shown in the top-left corner of the plot. As in the Hyperboloid observations discussed in Section 3.1.1., three distinct populations are evident in the TIDE distributions: outflowing ionospheric beams flowing in the direction anti-parallel to the magnetic field ($-V_X$); a nearly isotropic warm population (green), and a population of cold ions flowing toward the dusk ($-V_Y$). The computed moments of the distribution are shown at the bottom-left corner of the plot. It should be noted that the moment calculation is limited to restricted regions in energy, spin azimuth, and polar sectors, as labeled on the plots, in order to better estimate the duskward core population.

Seen in the bottom two panels of Figure 3a are one-dimensional cuts through the two-dimensional distribution function in planes where V_Y ~−52 kms^{-1} (left) and V_X ~0 (right). In each case, the distribution functions are a composite of two populations. The blue and red lines represent the estimated magnetosheath and plasmaspheric distribution functions, respectively, obtained by the method described in Section 2. The modeled magnetosheath PSDs match rather well with the observed PSDs where $|V_{X\ or\ Y}| \geq 100$ km s^{-1}. We should note here that the estimated magnetosheath distribution has not been shifted to the earth frame as was done with the observed distribution. The purpose of our comparison is to confirm that the observed magnetosheath PSD is of at least the same order (or lower) as the estimated PSD of the core magnetosheath distribution. The plasmaspheric density and temperature are assumed here to be 5 cm^{-3} and 10 eV, respectively. The center velocity of the plasmasphere population has been shifted to achieve a better match with observations. The estimated plasmaspheric PSDs are similar to the observed PSDs where $|V_{X\ or\ Y}| \leq 100$ km s^{-1}.

Based on the reconnection scenario presented by *Gosling et al.* [1990], a duskward flow of reconnected flux tubes should be observed when the observer is located above the reconnection point and the Y component of the interplanetary magnetic field (IMF) is negative. For the case shown in Figure 3a, measurements from the Wind spacecraft confirm that the IMF B_Y was indeed negative during this time period. The duskward flow direction of the cool material in Figure 3a is thus consistent with our expectation for plasmaspheric material being transported on open field lines.

During the time period discussed here, the *Kp* index was only 2−; however, it had been as high as 3+ three days prior to the event. This may suggest that the plasmaspheric material may have drained toward the dayside earlier and remained for several days waiting for right conditions to participate in the reconnection process and be transported to the high-latitude region.

3.2.2. May 14, 1996

In this event, the electron and ion measurements from HYDRA indicate slightly different locations of the open-closed field line boundary. By ~11:22 UT, however, the satellite had clearly entered the open field line region. At this point, magnetosheath ions and electrons were observed by HYDRA while plasma sheet ions and electrons were absent (not shown here). On the day prior to this event, the *Kp* index was up to 4−. In Figure 3b, two-dimensional PSD distribution function (top) and one-dimensional cuts (bottom) are shown from 11:23−11:24 UT. The format is identical to that of Figure 3a. Ionospheric outflows were not observed during this time period, and the cold population was in the direction parallel to the magnetic field (i.e. downward toward the ionosphere). The moments, as given in the bottom-left corner of the plot, are calculated only in restricted regions in energy, spin azimuth, and polar sectors for a better estimation of this downward core population.

In the bottom panels of Figure 3b, the cuts through the two-dimensional PSD distribution function are taken where V_X ~70 km s^{-1} (right) and where V_Y ~0 (left). At energies above its threshold of 15 eV, the Polar/TIMAS instrument observed a PSD distribution very similar to that shown for TIDE in Figure 3b. The estimated magnetosheath PSDs (blue lines) match the observed PSDs for the warmer portion of distribution function. For the modeled plasmaspheric distribution function, we used a bi-Maxwellian to give a better fit with the data. The plasmaspheric density, parallel temperature, and perpendicular temperature that yielded the good fit to the observations shown in Figure 3b were 14 cm^{-3}, 10 eV, and 20 eV, respectively. The center velocity of this plasmasphere population has been shifted to match the observations. As was seen in the previous cases, the estimated plasmaspheric PSDs are similar to the observed

PSDs for the cold population of the distribution function, an indication that plasmaspheric material was observed on reconnected field lines.

In addition to the two events described above, plasmaspheric material being transported on high-latitude open field lines was also observed in two other TIDE events: at 02:18:10–02:19:20 UT on May 21, 1996 and again from 04:28 to 06:45 UT on May 29, 1996. These two cases have also been confirmed according to our PSD comparison. *Chandler et al.* [1999] presented data from the event on May 29. They explained the downward core population observed by TIDE, with temperature ~2 eV, to be ionospheric origin reflected at the magnetopause. The downward D-shape magnetosheath ions together with this downward core population were due to component merging equatorward of the cusp. The absence of low-speed anti-parallel ions is due to a several-volt positive spacecraft potential. Since the energy of typical cusp outflows at 6–8 R_E is higher than the spacecraft potential 3–4 V (lowest spacecraft potential during 04:28–06:45 UT on May 29 observed by the Electric Field Instrument on board Polar), ion outflows with energy below 400 eV should probably have been detected by TIDE if present. Therefore, the core downward population observed in this case is not due to ions reflected directly from ionospheric outflows; rather, they are indicative for plasmaspheric ions originating from the ionosphere then being transported on reconnected field lines.

4. Discussion and Conclusion

Twenty months of Hyperboloid observations have yielded twenty-one events in which the Interball Auroral Probe passed through open field lines on the dayside while increased geomagnetic activity was observed. In two of these cases, evidence of plasmaspheric material was found with our PSD comparison. An additional four such events were identified from eleven months of TIDE observations.

Draining plasmaspheric material is expected on reconnected field lines when the convection electric field suddenly increases which is a fairly common occurrence. However, despite a concerted search, only a few examples of such material have been found in satellite observations. Why is the occurrence frequency so low? One possible explanation is due to the fact that draining plasmaspheric material may not always participate in the dayside reconnection. It is possible that the material may be captured at the low-latitude boundary layer and then convected on closed field lines along the flanks of the magnetosphere. Secondly, the satellites might not always pass through the localized flux tubes, which contain draining plasmaspheric material. A third possibility is that plasmaspheric material is energized (heated) by the reconnection process or by an energy exchange with the magnetosheath plasma after the flux tubes are opened, making it extremely difficult to differentiate from magnetosheath material. As shown in the bottom two rows of Table 1, peak PSDs for energized plasmaspheric ions (40 eV and above) are on the order of 10^8 or 10^9 $km^{-6}s^3$, comparable to the estimated and observed magnetosheath PSD in this energy range. As a result, the energized plasmaspheric ions become difficult to identify from the entering magnetosheath. Observations of heavy ions (He^+ and O^+ of magnetospheric origin) could help in resolving these questions; however, this is a difficult task in itself. For example, the density of heavy ions may be too low to provide accurate measurements from satellite instruments. This fact was evident in each of the Hyperboloid cases presented in Section 3.1 when O^+ ion counts were detected in addition to the O^+ ionospheric outflows. While signatures of outflows were extremely clear, O^+ counts in the downward and perpendicular directions were ambiguous. Furthermore, spurious counts of heavy ions may result from the detection of H^+ ions. This was often seen in the data collected by TIDE.

The circulation of plasmaspheric material in the Earth's magnetosphere was suggested by *Freeman et al.* as early as 1977; however, this paper is the first to present observational evidence of plasmaspheric material being transported on high-latitude reconnected field lines. The PSD comparisons help us to screen-out plasmaspheric material from the low-energy portion of magnetosheath. Although the occurrence frequency is low, evidence of cold plasmaspheric material being transported on high-latitude open field lines does exist.

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Figure Captions

Plate 1. (top) H^+ energy-time spectrogram observed by Hyperboloid from 18:10 to 18:40 UT on March 10, 1998. The universal time (UT), local time (LT), invariant latitude (ILAT), and satellite altitude (ALT) are shown on the horizontal axis. The energy flux is color-coded according to the color bar. (bottom 4 panels) H^+ spectrograms from 18:12 to 18:28 UT for energies 30–80, 12.5–30, 5–12.5, and 0–5 eV, respectively. The vertical axis represents 16 instrument sectors. Squares, crosses, and solid lines (wave structures) represent directions parallel, anti-parallel, and perpendicular to the local magnetic field, respectively.

Plate 2. (top) H^+ energy-time spectrogram observed by Hyperboloid from 17:30 to 18:30 UT on December 30, 1997. (bottom 4 panels) H^+ spectrograms from 17:30 to 17:50 UT for energies 30–80, 12.5–30, 5–12.5, and 0–5 eV, respectively. The format of Plate 2 is the same as that of Plate 1.

Figure 1. An example of PSD distribution functions for magnetosheath source (solid line) and plasmapsheric source (dashed line).

Figure 2. (a, top) Two-dimensional PSD distribution function observed by Hyperboloid from 18:22:30 to 18:24:30 UT on March 10, 1998. The horizontal and vertical axes represent perpendicular and parallel velocities, respectively. PSD is color-coded according to the color bar. (a, bottom) A One-dimensional PSD distribution function slice in which the parallel velocity ~0 on the top panel. Solid circles, a blue line, and a red line are used to represent the Hyperboloid data, modeled magnetosheath PSD distribution function, and estimated plasmaspheric PSD distribution function, respectively. (b, top) Two-dimensional PSD distribution function observed by Hyperboloid from 17:42 to 17:44 UT on December 30, 1997. (b, bottom) One-dimensional

PSD distribution function sliced at which the parallel velocity ~0 on the top panel. The format in panel b is the same as that described for panel a.

Figure 3. (a, top) Two-dimensional PSD distribution function in V_Y–V_X plane observed by TIDE from 14:08 to 14:09 UT on April 30, 1996. Positive V_X is in the direction parallel to the local magnetic field, while positive V_Y is the normal direction of Polar orbit plane. PSD is color-coded according to the color bar. The spacecraft potential, distance between the satellite and the Earth, L-shell, magnetic local time (mlt), magnetic latitude (mlat), and invariant latitude (invlat), ranges for TIDE moment calculation, and moments are shown on the left. (a, bottom) One-dimensional PSD distribution function slice in which (left) $V_Y \sim -52$ kms^{-1} and (right) $V_X \sim 0$. Solid circles, blue lines, and red lines are used to represent the TIDE data, modeled magnetosheath PSD distribution function, and estimated plasmaspheric PSD distribution function, respectively. (b, top) Two-dimensional PSD distribution function observed by TIDE from 11:23 to 11:24 UT on May 14, 1996. (b, bottom) One-dimensional PSD distribution function sliced in which (left) $V_Y \sim 0$ and (right) $V_X \sim 70$ kms^{-1}. The format of panel b is the same as that used in panel a.